FPRS FOREST PRODUCTS JOURNAL
VOL. 16, NO. 1
JANUARY 1966

Cutting Characteristics of Chain Saw Teeth[1]

S. C. Gambrell, Jr.
University of Alabama
University, Ala.

E. F. Byars
West Virginia University
Morgantown, W. Va.

THE PURPOSE of this research was to investigate the mechanics of cutting wood with chain saw teeth. This work consisted of the design, construction, instrumentation, and testing of a machine capable of measuring the forces existing on and the energy requirements of a single chain saw tooth as it cut through green timber in a radial direction. The long-range objective of this investigation is to provide basic information leading to an improved tooth design giving greater efficiency when cutting a particular species of timber.

For years, chain saws have been used to fell and buck vast amounts of timber throughout the world, but basic research on the mechanics of cutting with chain saw teeth has been quite limited. In contrast, McKenzie (1,2,3), Franz (3,4), Reineke (5,6,7), Walker (8), and others have conducted extensive studies of cutting with single planer-type cutting tools, and they have determined the effects of cutting speed, depth of cut, and various cutting angles on cutting force, energy consumption, and chip formation. This type of information about chain saw teeth is extremely scarce. This dearth of knowledge has been somewhat relieved by Randel (9), McKenzie (10), and Oehrli (11) in their investigations of the overall power requirements and cutting efficiency of complete saw chains or multitooth devices. Troeng (12) used a pendulum technique similar to that of Reineke (5) in a limited investigation of the work done when cutting with a single chain saw tooth. Much basic research is needed to evaluate the effects of the several parameters involved in chain saw tooth design on cutting forces and energy requirements.

This research was conducted to develop a suitable technique for measuring those forces and energy requirements and to determine their magnitudes in a restricted study of one type tooth cutting one species of timber. Since a radial cutting direction is most commonly encountered in chain saw operation, high-frequency-response force transducers were designed to measure accurately the forced oscillations of the saw tooth caused by cutting across the grain struc-

[1]The research for this paper was supported in part by the Northeastern Forest Experiment Station, U.S. Forest Service, and in part by the National Aeronautics and Space Administration.

Abstract

This research was planned to investigate the mechanics of cutting wood with chain saw teeth with the hope that the results will lead to more efficient tooth and overall saw designs based less on intuition and more on rational analysis. This work consisted of the design, construction, instrumentation, and testing of a machine capable of measuring the forces existing on and the energy requirements of a single chain saw tooth as it cut through green timber in a radial direction.

A variable-velocity whirling-arm wood-transport machine was combined with the power feed table of a milling machince to provide a selection of speeds and depths of cut. This combination provided a limited range of feed rates and cutting angles. High-frequency-response force transducers and a capacitance-displacement transducer were used to obtain energy consumption per cut and average cutting force in three principal directions. Cutting forces and energy were measured over a speed range from 500 to 3,640 feet per minute at depths of cut from 0.010 to 0.060 inch. High-speed photographs of chip formation were taken to identify and define the type of chip related to the depth of cut.

Data are presented showing cutting force and energy consumption as a function of cutting speed and depth of cut when cutting green red oak with chipper-type saw teeth. The effects of cutting angle on energy consumption and the relative magnitudes of the shearing and planing components of the longitudinal force were determined. Results were correlated with the relationship between the wood fiber structure and the components of the saw tooth, and they indicated that the three principal cutting forces increased appreciably with increased depth of cut and decreased slightly with increased cutting speed. Energy consumption was relatively independent of cutting angle, and the planing component of the longitudinal force produced the greater energy consumption. Chip formation was dependent upon depth of cut and independent of cutting speed.

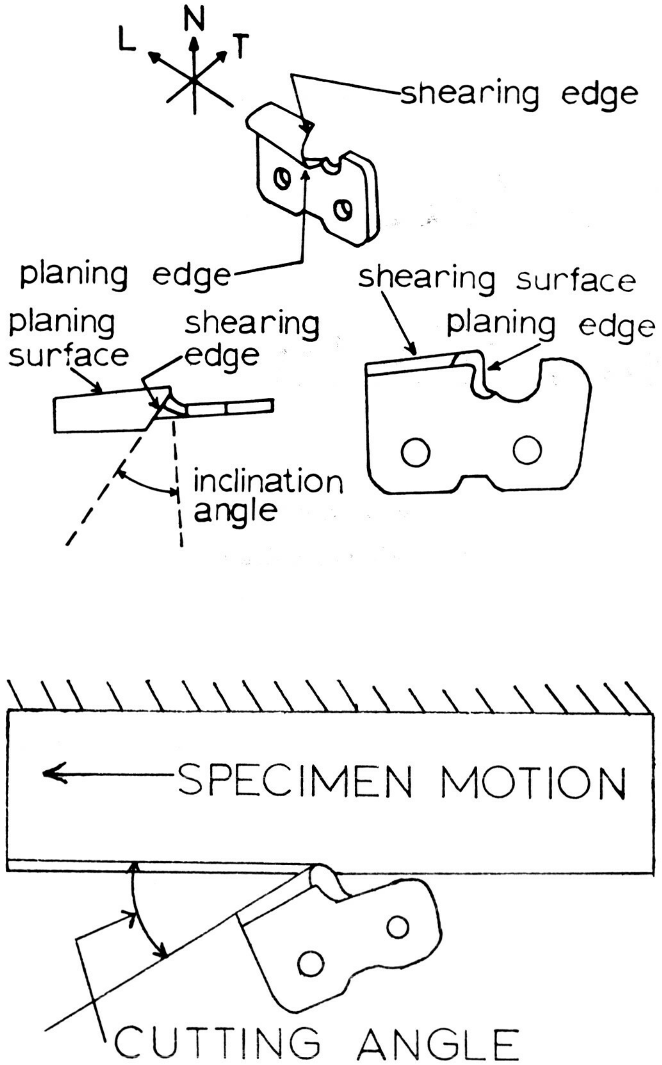

Figure 1. — Top: detail of chain saw tooth and definition of the three principal directions: longitudinal (L), transverse (T), and normal (N). Bottom: Definition of cutting angle.

ture. Tests were limited to cutting red oak (*Quercus rubra*) with an Oregon chipper 7/16 inch pitch saw tooth in a true radial direction. Three directions relative to a chain saw tooth were defined as longitudinal, transverse, and normal; and the shearing and planing components of the saw tooth were identified (Figure 1, top). To include and exceed the cutting speeds and depths of cut used today in chain sawing, cutting speeds from 520 to 3,640 feet per minute and depths of cut from 0.010 to 0.060 inch were used. Since the total cutting time per tooth was approximately 1.5 seconds, edge dulling was not considered in this study. Saw teeth were used as received from the manufacturer. Tests were conducted to determine 1) average longitudinal force and energy consumption, average transverse force, and average normal force as functions of cutting speed and depth of cut; 2) energy consumption for the shearing and planing components in the longitudinal direction; 3) effects of cutting angle on energy consumption; and 4) effects of cutting speed and depth of cut on chip formation.

It was not the purpose of this study to obtain data necessary for a complete analysis of cutting with chain saw teeth, but rather to develop and establish a means to obtain information about the cutting process and to conduct an initial study of the effects of several major parameters on cutting forces, energy requirements, and chip formation.

The real value of this work, therefore, lies not in the gross amount of wood cutting information obtained but in the development of a method and technique to accurately measure the transient, fluctuating cutting forces and energy consumption. Plans have been made to use the equipment and measuring techniques developed for this investigation in a continuing, more detailed study of the factors involved in cutting wood with chain saw teeth. Since the cutting tests were limited in scope, no far reaching or all-encompassing conclusions were drawn from the results, and all statements were restricted specifically to the range of variables tested.

The explanations and statements presented in the results, discussion, and conclusions of this paper are the considered opinion of the authors and represent the analysis of data from an engineering point of view. Since this was the initial investigation into the cutting action of chain saw teeth, some of the statements were necessarily based on opinion rather than extensively documented fact. It is anticipated that future work may further confirm these opinions.

Equipment

Test Machine

An 8-foot diameter whirling-arm wood-transport machine similar to that used by Walker (8) having a speed range of 260 to 5,000 feet per minute was used in synchronization with the power-controlled feed table of a milling machine (Figure 2). A variable speed d.c. motor drove the whirling arm through an intermediate shaft arrangement giving a 9 to 1 speed reduction. The chain saw tooth was attached to a force transducer mounted on an adjustable base plate, which was bolted to the feed table of the milling machine. Depth of cut was controlled by synchronizing the whirling-arm rotation with any one of 12 feed rates of the milling machine table. The machine was securely anchored to a load floor and completely enclosed in a steel safety shield. The wood specimen was mounted on the end of the whirling arm at a cutting radius of 49-$\frac{3}{4}$ $\pm$ $\frac{1}{4}$ inches and was cut along a 4-inch length in an essentially linear cutting path. Since both right- and left-handed cutters are required in chain sawing, a second non-instrumented tooth was mounted on the milling machine table to complete the cut and form the kerf. Cutting speed was controlled with a continuously recording tachometer.

Force Measurement

Preliminary cutting tests indicated that forces of slightly less than 100 pounds in the longitudinal direction, + 30 to -10 pounds in the transverse direction, and $\pm$ 10 pounds in the normal direction were to be expected. In addition, based on the average ring count for red oak of 9.9 rings per inch (13), forced oscillations of up to 6,500 cycles per second caused by cutting radially across the grain would occur and had to be measured accurately. A three-force transducer using the closed-ring principle used by Loewen (14) and Cook (15) was designed incorporating the required sensitivity in all three principal directions. Incorporating the sensitivity requirements, however, resulted in a non-acceptable low-frequency-response characteristic. It was also quickly realized that the construction of a three-force transducer with a necessary sensitivity and 8,000-plus cycle-per-second natural frequency was impractical if not impossible. Therefore, it was resolved to measure the three principal forces independently.

The transducer that best met the requirements of sensitivity and frequency response for measuring the longitudinal force was a 30° or 45° angle design machined from 1/4 inch 2024-T3 aluminum alloy plate (Figure 3). The 30° and 45° transducers had natural frequencies of

11,540 and 8,000 cycles per second, respectively. Saw teeth were mounted on a 1/16-inch thick tang with standard chain saw rivets and side links. The high sensitivity required to accurately measure the low forces in the transverse and normal directions dictated that lower natural frequencies must be accepted in the transverse and normal transducers. Referring to Figures 1, bottom, and 17, one can see that the cutting edge of the saw tooth did not sever wood fibers in the normal and transverse directions, while in the longitudinal direction, the planing and shearing edges of the tooth severed or crushed the fibers as the wood moved relative to the tooth. Forced oscillations of the tooth, however, did occur in the normal and transverse directions and were attributed to the tooth dragging across the grain structure rather than to severance of wood fibers. Therefore, since oscillations in the normal and transverse directions did not occur as a direct result of fiber severance, frequency response of the normal and transverse transducers was considered less critical than the response of the longitudinal transducer. A cantilever design for transverse force measurement and a saddle-beam design for normal force measurement provided the necessary sensitivity and had natural frequencies of 2,100 and 3,500 cycles per second, respectively (Figure 4). Resistance strain gauges, whose output was fed into one channel of a dual channel oscilloscope, were bonded to the sensing sections of all transducers in full bridge circuits, and bridge voltage was obtained from a 12 volt 65 ampere-hour battery. Bridges were wired to be insensitive to forces other than the one in the particular direction being measured.

The chief aim in all transducer designs was to obtain the best possible combination of sensitivity and frequency response. The accurate measurement of the force variation caused by cutting *across* the grain structure (as in a normal chain saw cut) dictated that transducers with high natural frequencies be constructed but, at the same time, be capable of resolving forces of as little as ½ pound or less. Preliminary cutting tests showed that all transducers vibrated during the cut at their natural frequencies, due to excitation by the frictional component of the cutting force created by the saw tooth rubbing against the kerf walls. This action was similar to that of a violin string under excitation by the bow. These natural-frequency vibrations produced traces on the oscilloscope screen that were difficult to interpret. Because we wanted to accurately record the forced oscillations caused by cutting across the grain and not the high natural-frequency oscillations, a variable cutoff band-pass electronic filter was used between the sensing bridge and the oscilloscope to separate the two frequencies. This method of separation proved to be satisfactory, and excellent correlation was obtained between the recorded oscillations and the grain structure. The effect of filtering on the signal rise-time was measured, and no adverse effects on rise time could be detected at the relatively low oscilloscope sweep speeds necessary to record the entire 4 inch cut.

Displacement Measurement

The determination of energy consumption per cut required the measurement of displacement as well as force. A displacement transducer operating on the capacitance principle was designed incorporating a fixed plate mounted on the machine

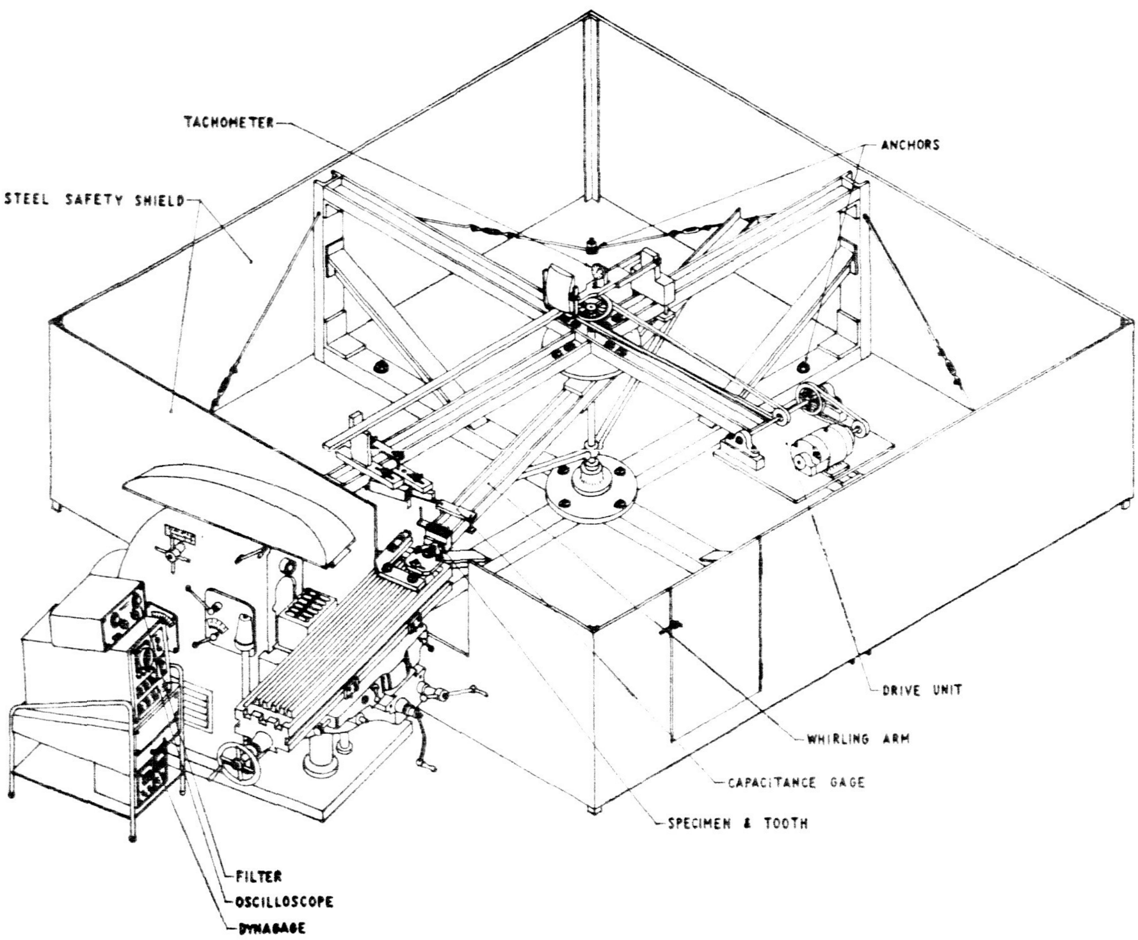

Figure 2. — Detail of apparatus used for cutting tests showing whirling arm, milling machine, and related instrumentation.

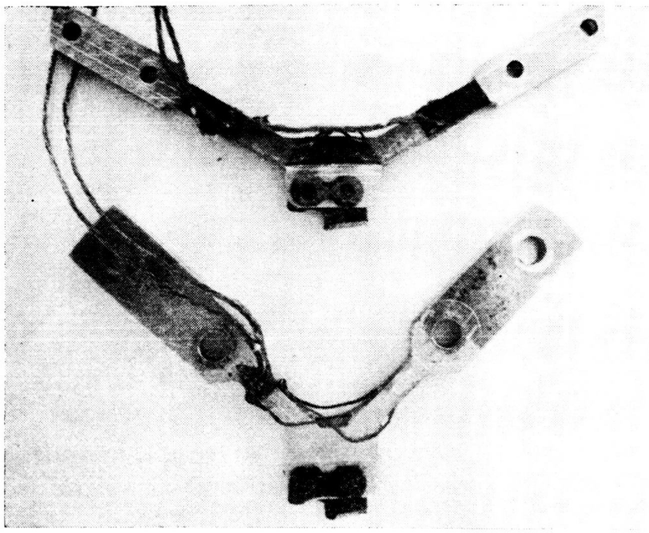

Figure 3. — The 45° and 30° angle transducers used for measuring longitudinal force and energy consumption.

frame and a moving plate mounted on the whirling arm. The capacitor plates were connected with a probe and cable to a tunable oscillator-detector circuit in which small changes in capacitance produced large changes in the diode-detector impedance. The detector output was, therefore, proportional to the changing area between plates and hence to displacement. The displacement transducer was adaptable for either displacement-time or force-displacement measurements. Both types of measurements were made in this investigation.

Instrumentation for Chip Formation

High-speed photographs were taken of the tooth as it cut through the wood. These photographs were taken in ambient total darkness using a strobotac with a single flash and flash-delay attachment providing a 3 microsecond flash duration. The position of the tooth relative to the wood specimen could be adjusted with the flash delay, and the strobotac was triggered to flash at the right moment by the reflection of light from a photoelectric cell incident upon a piece of reflective foil tape attached to the whirling arm (Figure 5).

General Instrumentation and Procedure

The components of the measuring system used had selectivity, sensitivity, and frequency-response characteristics exceeding those deemed necessary for this investigation. The major components of the signal conditioning and readout equipment used were: dual beam oscilloscope Tektronix Model 502A, filter Allison Model 2A (passive), Dynagage Photocon Model DG-605 (with PS-605 power supply), and a strobotac General Radio Model 1531-A. Attempts to measure the output of the force transducers with Tektronix Type Q and Type E units were unsuccessful because of unacceptable frequency-response characteristics and because a sharply filtered signal was necessary to eliminate the natural-frequency oscillations of the transducers.

Data collection involved setting the milling machine and electronic filter for proper feed rate and filter level, and then bringing the whirling arm up to speed. The feed lever of the milling machine was advanced, and the oscillophotograph was taken on the second cutting pass of the whirling arm. Sampling the second cut insured a true rather than a partial depth of cut. An electronic trigger circuit was used to simultaneously initiate the oscilloscope sweep on both channels at the proper instant prior to contact of the saw tooth with the wood specimen. The force-time, displacement-time, or force-displacement oscillophotographs were planimetered to obtain energy per cut or average cutting force. Four replicates of each cutting observation were taken, totaling 448 oscillophotographs for the complete study. Data were plotted to indicate both the average value and the range of variation of the data.

Specimen Preparation

Specimens were selected from the heartwood portion of a freshly felled red oak tree so that the cutting test was made in a true radial direction from bark to pith. Moisture content of the 12 specimens was 78.4 ± 3.1 percent, density was 0.628 ± 0.014 gram per cubic centimeter, and radial ring count was 6.58 ± 0.17 rings per inch. Specimens were sealed in plastic bags to prevent drying before use. As a further precaution against drying, specimens were dipped into paraf-

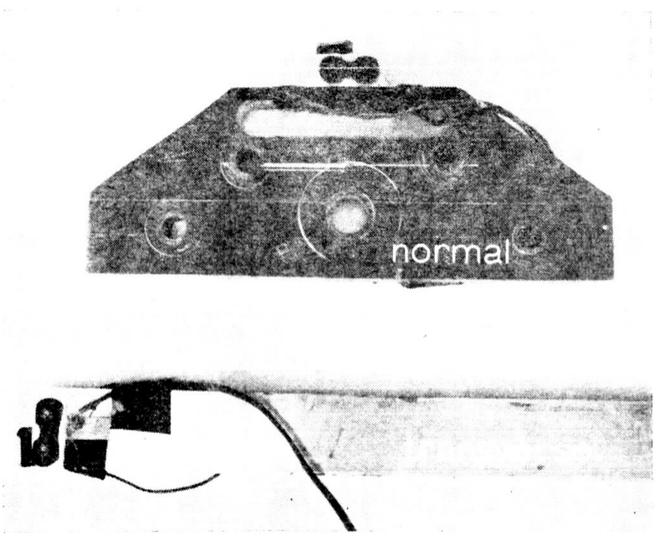

Figure 4. — Normal and transverse force transducers.

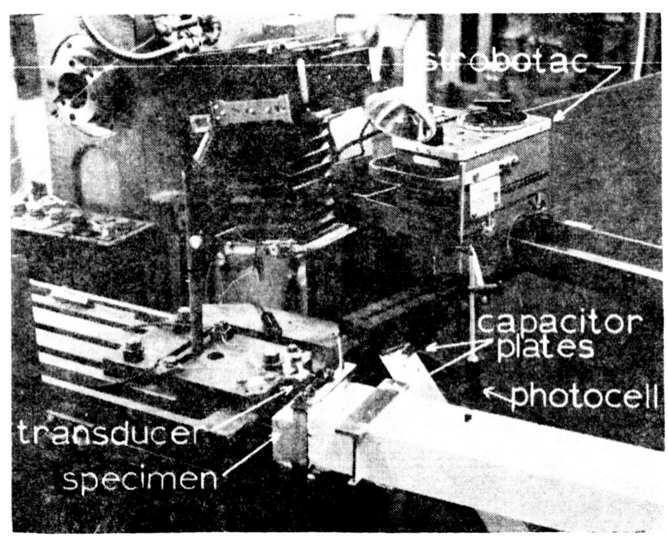

Figure 5. — Equipment used for high-speed photography. Note force and displacement transducers and wood specimen mounted on whirling arm.

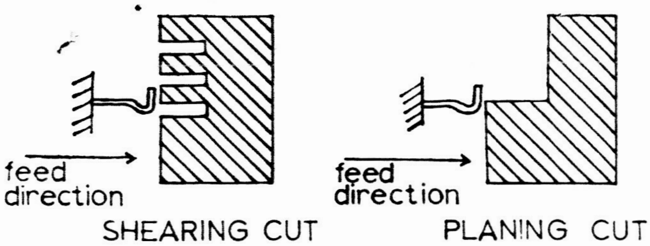

Figure 6. — Sketch of specimens used to obtain the shearing and planing components of longitudinal energy.

fin at 240° F. for 10 seconds immediately prior to the cutting test. The paraffin bond was good except along the end grain. Since strength and mechanical properties of wood have been shown to be independent of moisture content above the fiber saturation point (16,17,18), moisture content was not considered as a variable in this investigation.

Cutting Situations

Cutting Angle

Geometric characteristics of a chain saw tooth make it difficult to define precisely the cutting method in the common terms used for metal cutting (19). The chain saw cutting action can be best described as a combination of modified orthogonal and oblique cutting. The planing edge on a properly sharpened chain saw tooth is usually perpendicular to the cutting velocity vector and thus produces a form of orthogonal cut, while the shearing edge has an inclination angle relative to the cutting velocity vector and thus produces a form of oblique cut (Figure 1, top). In chain saw cutting, the planing edge rake angle remains reasonably constant in any cutting situation, due to the restriction of the drive link sliding in the cutter bar guide, while the shearing edge rake angle varies dependent upon the motion of the complete cutter bar and the rotation of the saw tooth with respect to the cutter bar in the plane of the cutter bar. Here again, due to geometric characteristics of the chain saw tooth, rake angle is not a precise term as it is in metal cutting. In this study, the general term "cutting angle" defined the position of the shearing surface of the chain saw tooth relative to the cut surface of the wood specimen (Figure 1, bottom).

Energy Components

Tests were conducted to determine the contribution of the shearing and planing edges of the saw tooth to the total energy consumption per cut in the longitudinal direction as a function of depth of cut. The two components were isolated and measured by special machining of the wood specimen to measure one cutting component at a time (Figure 6). In addition to gaining information about the relative magnitudes of the energy components, the two measured component values were compared with the total energy consumption for a particular cutting situation to give an indication of the role friction played in the cutting process.

Chip Photography

High-speed photographs of the cutting process were taken to study the effects of cutting speed, depth of cut, and cutting angle on chip formation. A specially machined specimen was used to allow visual access to the saw tooth as it cut through the wood. This cutting situation differed from a standard chain saw cut since in the actual cut, the saw tooth is completely surrounded by wood fibers, while in these tests it was open on the top side. Although these tests did not represent the true cutting situation, it was felt that the basic characteristics of chip formation were not destroyed and that the photographs would provide valuable information about the study and definition of the different types of chip formation.

Results and Discussion

Longitudinal Direction (Direction of Wood Motion)

The high natural frequencies of the longitudinal transducers gave excellent frequency response to the forced oscillations caused by cutting across the grain throughout the entire range of cutting speeds (Figure 7). An exact correlation existed between the force peaks on the oscillophotograph and the number of annual rings in the wood specimen. Since no consistent trend occurred, no specific limits could be placed on the magnitudes of the force variation about the mean force. Fluctuations, however, were observed having magnitudes of from 5 to 75 percent of the mean cutting force.

The data plotted in Figure 8 indicate that cutting force and energy requirements in the longitudinal direction are dependent upon depth of cut and relatively independent of cutting speed. Other investigators using planer-type cutting tools have noted similar relations of cutting force to depth of cut and cutting speed (1,2,3,8). The slight decrease of force with increased speed at the deeper depths was a result of the relationship between the geometry of the planing edge and the cell wall structure. In comparison to the sharp, streamlined planer-type tools used by McKenzie (1) and Walker (8), the chipper chain saw tooth is a thick, relatively blunt cutting instrument. It is felt that as the cutting speed increased, the tendency to crush the cell walls with the thick planing edge decreased, and the tendency to sever the walls with the planing edge increased, therefore, explaining the lesser cutting force. This action can be visualized by imagin-

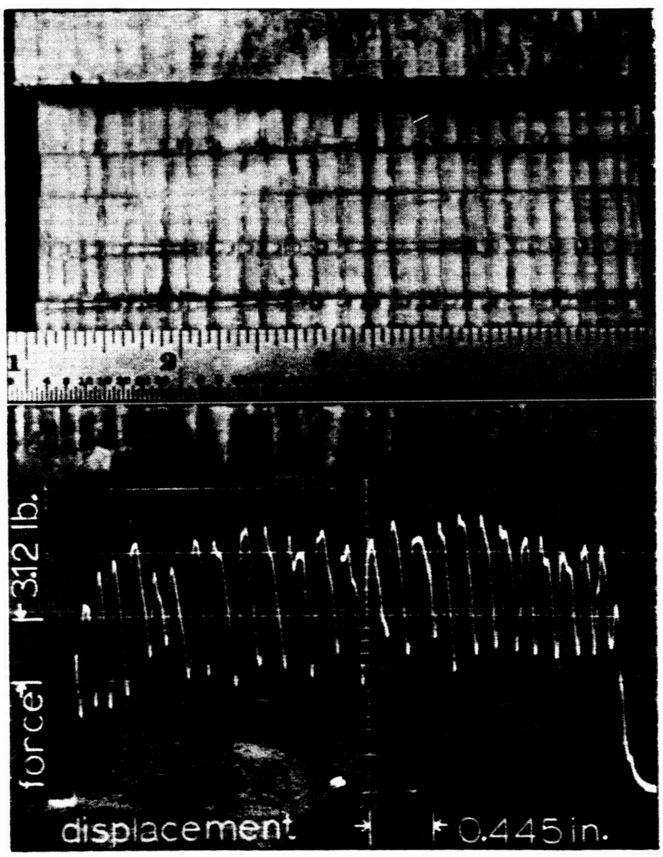

Figure 7. — Photograph showing the correlation between the grain structure and the longitudinal force peaks caused by cutting across the grain.

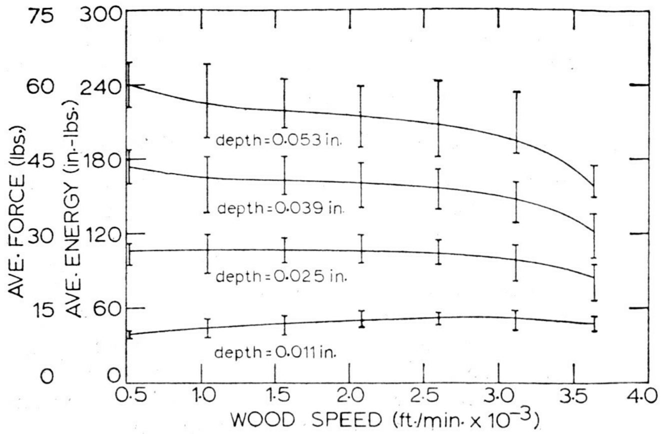

Figure 8. — Average longitudinal cutting force and energy consumption versus cutting speed for various depths of cut. Curves show both average values and range of variation.

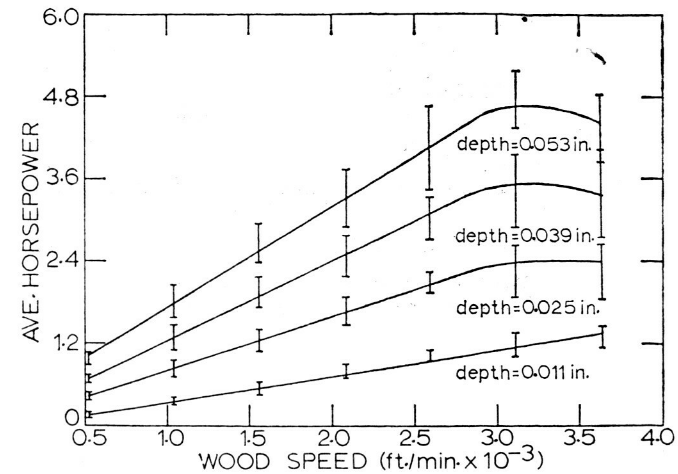

Figure 9. — Average horsepower versus cutting speed for various depth of cut. Note slight overlap in variation at higher speed.

ing the difference between cutting a taunt string with slowly applied and then with rapidly applied blows from a knife edge. It appears that at a depth of 0.011 inch, the planing edge contributed very little to the cutting action, and the cutting force remained practically constant due to wedging the wood cells apart with the shearing edge, rather than cutting them with the planing edge.

The rapid decrease of cutting force above a cutting speed of 3,000 feet per minute indicated the presence of a critical cutting speed where, in the authors' opinion, the tendency to crush the cell walls ceases and failure occurs entirely due to severance of the wood fibers by the planing edge. Since the upper limit of cutting speed was 3,640 feet per minute, however, no definite conclusions were made concerning the existence of or reasons for this apparent critical cutting speed.

A regression equation

$$E = -29.7 + 5091D + 0.03S - 49 \times 10^{-7} S^2 - 0.59DS$$

where E = energy per cut, inch-pounds, D = depth of cut, inches, S = cutting speed, feet per minute, was obtained from a computer analysis of the data and had a non-significant lack of fit at the 0.05 level in a standard F test. A multiple correlation index of 0.94 indicated that 94 percent of the total variation was explained by the regression equation. An equation

$$F = -7.44 + 1275D + 75 \times 10^{-4} S - 12.5 \times 10^{-7} S^2 - 0.147DS$$

where F = average cutting force, pounds, was obtained by dividing the coefficients of the energy equation by the number 4 corresponding to the length of the wood specimen. Curves expressing horsepower as a function of cutting speed and depth of cut were obtained by dividing energy consumption per cut by time per cut. A regression equation

$$HP = -0.69 + 10.5D + 91 \times 10^{-5} S - 17 \times 10^{-8} S^2 + 17.4 \times 10^2 D^3 + 19 \times 10^{-3} DS$$

plotting the family of curves in Figure 9 was obtained with the computer and had a non-significant lack of fit at the 0.05 level with a multiple correlation index of 0.946. These equations were obtained by trying various combinations of depth and speed and testing them against the experimental data for lack of fit in a multivariable regression analysis. In no way do the above equations represent a unique set of variables for approximating the relations between energy, horsepower, speed, and depth.

Transverse Direction (Parallel to Wood Cells, Perpendicular to Direction of Wood Motion)

Due to the relatively low natural frequency of the transverse transducer (2,100 cycles per second), the amplitudes of the forced oscillations caused by the grain structure were attenuated at cutting speeds above 1,560 feet per minute. As speed increased above this figure, attenuation increased proportionately, and as a result, the force-time traces at the higher speeds did not show the well-defined force peaks but were indicative of only the averaged force (Figure 10). Even though no grain structure was cut by a cutting edge in a transverse direction, the saw tooth did vibrate in a direction perpendicular to the cutter bar at a frequency correlated with the grain structure, due to the planing surface of the saw tooth dragging across the grain.

Figure 11 shows that the transverse cutting force was dependent upon both speed and depth, with speed being the least prominent variable. The direction of the transverse force was always positive, indicating that the tooth rode on the surface of the parent wood primarily because of the forces created on the curved surface of the planing edge as the tooth was forced into the wood specimen at the feed rate set on the milling machine. As the saw tooth was fed into the wood under cut, the curved surface caused the tooth to deflect in the positive transverse direction perpendicular to the direction of feed. The tendency for negative transverse deflection, due to the effects of the sharpness and inclination angles, was not sufficiently large to overcome the effects of the curved surface, and thus the transverse force steadily increased with depth of cut.

The undulating characteristics of these curves can be attributed to the condition of the surface of the parent wood upon which the planing surface of the saw tooth rode during cutting. This surface was scalloped slightly by the digging action of the planing edge of the saw tooth. The tendency to dig in a transverse direction was only partially restrained since the relationship of the saw tooth to the 1/16 inch tang provided the greatest transducer flexibility in the transverse direction. No attempt was made to smooth the wood surfaces between successive cuts, and as a result, the planing surface of the saw tooth was subject to the effects of riding partially or completely on a peak, depending upon the previous and current depths of cut. The peak-to-valley amplitude of these scallops was small, being always less than 0.02 inch but it did affect the output of the transverse transducer.

Normal Direction (Tangent to Growth Ring, Perpendicular to Direction of Wood Motion)

The natural frequency of the normal transducer (3,500 cycles per second) provided excellent measurement of the normal force variations up to a cutting speed of 2,600 feet per minute. Above this speed, the amplitude of the oscillations was attenuated, and the oscillophotograph trace indicated only an averaged value of force (Figure 12). No cutting edge cut across the grain structure in a normal direction, but the saw tooth vibrated in a direction normal to and in the plane of the cutter bar, due to the shearing surface of the saw tooth dragging across the grain structure. At a cutting depth of 0.011 inch, the normal force on the tooth was directed toward the milling machine or away from the wood, while at depths of 0.025 inch or greater, the normal force was directed toward the specimen, indicating that the saw tooth was actually pulling itself into the wood (Figure 13). The tendency to feed itself into the wood at the deeper depths can be attributed to the pulling effects of the sharpness angle of the shearing edge and the cutting angle of the tooth, while at the lesser depths of cut, these angles cannot exert any appreciable force causing the tooth to feed itself, and thus the shearing surface of the saw tooth tends to ride on the parent wood.

The decrease of the normal force at the higher speeds and cutting depths was attributed to the increased feed rate pushing the saw tooth into the specimen. At these higher speeds and depths, the normal force exerted on the tooth by the feeding action of the milling machine tended to overcome the pulling force caused by the sharpness and cutting angles of the tooth, and thus the net force was reduced. At the very low cutting speeds where feed rate was small, the sharpness and cutting angles of the shearing edge exerted relatively large pulling forces on the saw tooth at the deeper depths.

It should be emphasized that the feed rate capabilities of the milling machine were not nearly as large as those found in actual chain saw operation. Therefore, it is quite feasible to expect that the normal force on the tooth would quite often be away from the wood. Note that the measurement of normal force on a chain saw tooth often requires measuring the force in the presence of other forces 4 to 20 times as large.

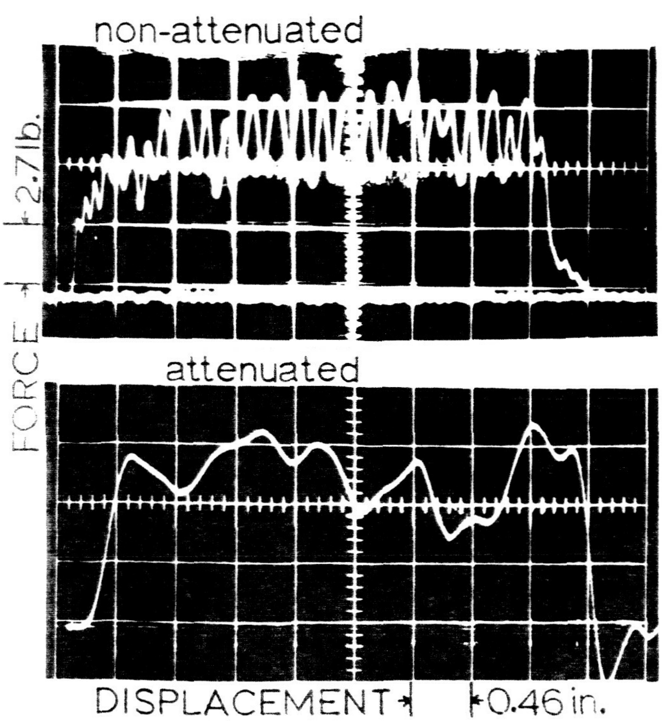

Figure 10. — Photograph showing forced oscillations in transverse direction due to cutting across the grain structure Top: non-attenuated trace shows results of cut at speeds within the frequency capability of the transverse transducer. Bottom: attenuated trace shows results of cut taken at speeds above the frequency capability of the transducer and indicates only the average value of force.

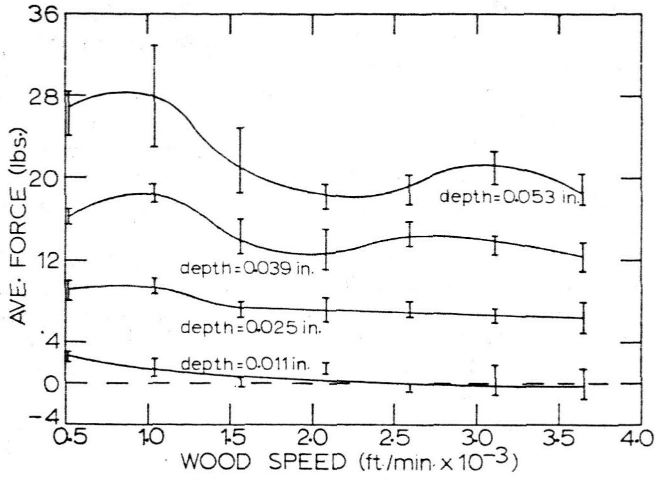

Figure 11. — Average transverse force versus cutting speed for various depths of cut.

Components of Energy

Results were obtained in this experiment that indicate the true tooth-wood relationship found in actual cutting with chain saws. An important relation was that a major portion of the total energy consumption was taken by the planing component and increased with depth of cut, while the shearing component remained at a low level and was independent of depth of cut (Figure 14). The points on the curve identified as "grasping friction" were obtained by taking the sum of the average values of the individually measured components of the longitudinal energy for a particular depth of cut and subtracting it from the average value of the previously measured total energy for the corresponding depth of cut. The word "grasping" was used because of the tendency for total envelopment of the saw tooth by the wood fibers in an actual cut, as opposed to the relatively open-type cut taken on the specially machined specimens used for the measurement of the longitudinal energy components.

It was noted that the sum of the average values of energy per cut for the shearing and planing components of the longitudinal energy at a depth of 0.010 inch exceeded the average value of the total energy per cut by 5.80 inch-pounds. Therefore, the grasping friction component at a depth of 0.010 inch was negative, indicating that the direction of the frictional force on the tooth was opposite to the direction of wood motion. This discrepancy obviously cannot exist and was explained by an approximately 1/64 inch overlap between the shearing and planing edges of the saw tooth while cutting the specially machined specimens. This overlap caused the energy consumption for both the shearing and planing components to slightly exceed their true value. Thus, the sum of the components exceeded the total energy consumption and resulted in the negative value for grasping friction at a depth of 0.010 inch. At this low depth of cut, both the transverse and normal forces were extremely small, and thus the grasping friction component was negligible.

The low, relatively constant value of the shearing component may possibly be explained by describing the relationship of the cutting edge to the wood fiber structure. The cellular growth of the wood fiber was parallel to the shearing edge of the saw tooth and thus, instead of actually cutting the wood fibers, the shearing edge tended to separate them by wedge action. This wedge action of fiber separation was independent of the depth at which the cut was made. One additional wood characteristic contributed to the low value of the shearing component. This characteristic was that of ray growth radially from pith to bark. It is known that the rays in wood are the weakest portion of the fiber structure in tangential tension, and this fact is apparent when the wood splits along the rays as it shrinks when drying. If the depth of cut was such that the cutting path of the shearing edge fell along a ray, the cellular fibers were wedged apart along their length, and again the shearing component of the longitudinal energy was small.

In like manner, the large, increasing values of the planing component may possibly be explained by observing the relationship of the planing edge to the cellular wood structure. The wood cell growth was perpendicular to the cutting direction of the planing edge, and thus the cells were physically severed or crushed by the planing edge as the cut was taken. In the deeper cuts, more cells were severed or crushed; therefore, the planing component of the longitudinal energy increased with depth of cut.

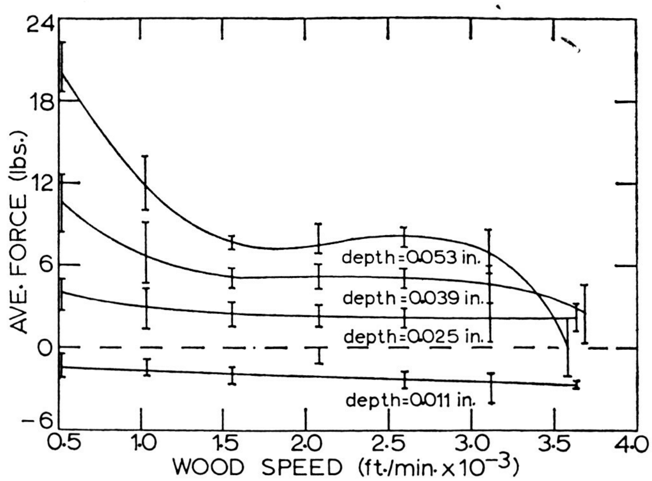

Figure 13. — Average normal force versus cutting speed for various depths of cut.

Cutting Angle

Tests indicate that the energy consumed by cutting in the longitudinal direction was relatively independent of the cutting angle of the saw tooth within the limits investigated (Figure 15). The tendency for a decrease in energy consumption between 6° and 15° may be attributed to a small decrease in frictional effects as the shearing surface of the saw tooth swings away from the parent wood, thereby decreasing the drag on the tooth, and to the decreased orthogonality of the planing edge with respect to the cell walls causing an increasing tendency to shear the walls rather than directly cut them. The apparent rising trend at 20° indicates that the increased cutting angle approached a value when the shearing edge was no longer functioning as a wedge separating the wood cells but was acting like a battering ram and producing separation by crushing and tearing.

Figure 16 indicates that the normal force became a more favorable self-feeding force as the cutting angle increased. This action may be explained by observing that, as the cutting angle increased, the sharpness and cutting angles were capable of exerting more force on the saw tooth toward the specimen, thus overcoming the force on the tooth caused by feeding into the wood. At a 0° angle, the cutting angle had no effect on the normal force, and the high negative normal force was caused by the flat shearing surface of the tooth pushing against the flat surface of the parent wood as the tooth was fed into the specimen.

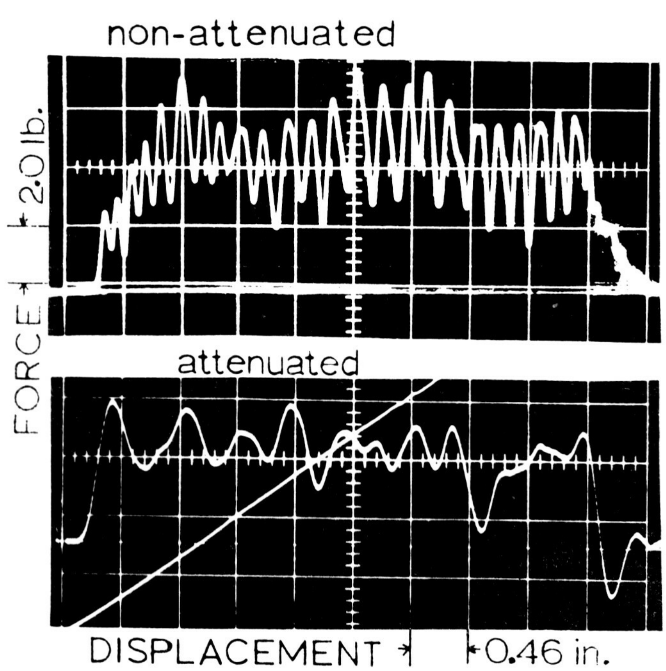

Figure 12. — Photograph showing forced oscillations in normal direction due to cutting across the grain structure. Top: non-attenuated trace shows results of cut taken at speeds within the frequency capability of the normal transducer. Bottom: attenuated trace shows results of cut taken at speeds above the frequency capability of the transducer and indicates only the averaged value of force.

Chip Formation

The mechanics of chip formation with chain saw teeth can be broken into two basic actions resulting from the cutting characteristics of the shearing and planing edges. The shearing edge, having an inclination angle, separates the cellular structure of the wood by wedge action and directs the resulting chip toward the cutter bar at an angle to the plane of the cutter bar. The planing edge, being essentially orthogonal to the cutting velocity vector, severs or crushes the wood cell walls and directs the resulting chip in a plane perpendicular to the cutter bar. This action produces a chip whose characteristics depend upon the depth of cut but not directly upon cutting speed. Figures 17a (1,040 feet per minute) and 17b (2,080 feet per minute) indicate that the basic chip type was independent of speed, and that speed affects only the relative direction in which the chip leaves the tooth. Figures 17b (0.010 inch depth) and 17c (0.050 inch depth) indicate that depth of cut greatly affected the type of chip formed. The cutting angle in Figures 17a through 17c was 6°.

Using the terminology of Walker (17), two types of chip were defined. The term "plastic" (Figures 17a and 17b) identifies a chip that tends to peel off the parent wood slightly ahead of the cutting edge in a curl 1/2 to 2 inches long before complete fracture. The term "riven" (Figure 17c) identifies a chip that tends to fracture well ahead of the cutting edge in a form of cantilever chip failing in tension, due to bending at the junction of the chip and parent wood. The riven chip fractures into short segments from 1/8 to 3/8 inch in length and is generally well shattered. That

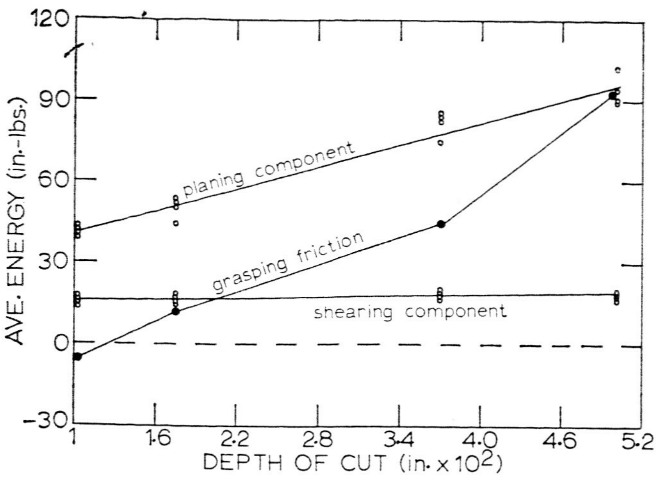

Figure 14. — Planing, shearing, and grasping friction components of energy versus depth of cut for a longitudinal cutting speed of 2,080 feet per minute.

portion of the chip separated from the parent wood by the planing edge was generally quite rough and jagged, indicating that considerable crushing of the cell walls occurred in the planing component of the cut. The transition depth between the plastic and riven chip was approximately 0.030 inch (Figure 17d).

Figures 17d (0° angle) and 17e (20° angle) show that the cutting angle did not affect the basic chip type but did have a considerable effect on the roughness of the sheared surface of the parent wood. Up to an angle of approximately 15°, the parent wood surface was reasonably smooth, indicating that wood cell separation occurred by wedge action with little crushing. At a cutting angle of 20°, however, the wood surface was extremely rough and jagged, indicating that separation occurred primarily by crushing and tearing apart the wood cells.

Examination of characteristic force-time oscillophotographs indicated that no high initial forces occurred upon impact of the cutting edge with the specimen. This lack of initial force can be attributed to the geometric relationship between the shearing and planing edges of the saw tooth and their relation to the initial contact with the wood. The inclined shearing edge meets the orthogonal planing edge at essentially a sharp point, which is the leading portion of the tooth making initial contact with the wood. The combination of a sharp-point contact with an extremely porous material eliminates the tendency for high-impact forces and causes the cutting edges to proceed smoothly into the wood, forming a fragmented chip continuous from the leading edge of the specimen to the cutting edges of the tooth.

Conclusions

Within the limits of this investigation, the following conclusions were made:

Within the range of cutting speeds and depth of cut used at the present time in chain sawing, the three principal cutting forces are independent of cutting speed. Within the entire range of this investigation, however, this statement is not true.

The planing edge accounts for from 46 to 72 percent of the total energy consumption, while the shearing edge consumes from 7 to 27 percent of the total energy.

An oblique planing edge would reduce energy consumption, since fiber separation would occur by shear action rather than by direct orthogonal severance.

Constructing the shearing edge of thinner material would reduce energy consumption, since wedging the wood cells apart with a thinner edge would require less force.

A square, rather than curved, junction between the planing and shearing surfaces would reduce the magnitude of the transverse force.

Chip formation is independent of cutting speed.

A cutting angle between 10° and 15° optimizes the cutting process with respect to energy consumption, operator effort, and fiber separation.

Recommendations

The following recommendations are made to provide more complete information related to the overall investigation of the cutting action of chain saw teeth:

Cross-grain cutting tests should be performed using only high-frequency-response transducers.

Using the present experimental design, a series of tests should be conducted to evaluate the effect of species and tooth type on cutting forces and energy requirements.

The effects of an oblique planing edge and a thinner shearing edge on cutting forces and energy consumption should be investigated.

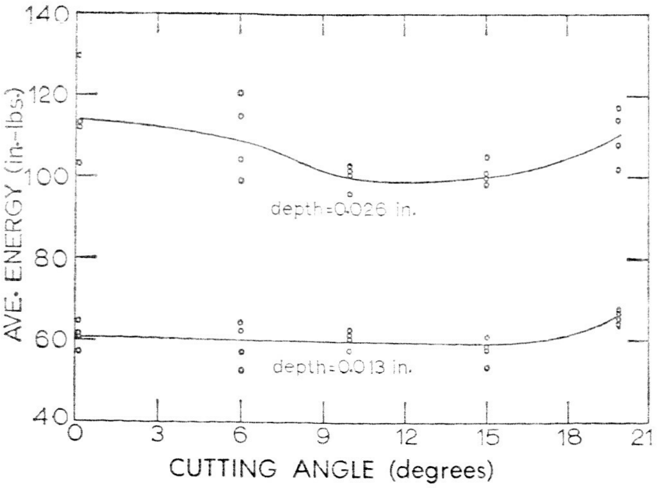

Figure 15. — Energy consumption in longitudinal direction versus cutting angle for two depths of cut.

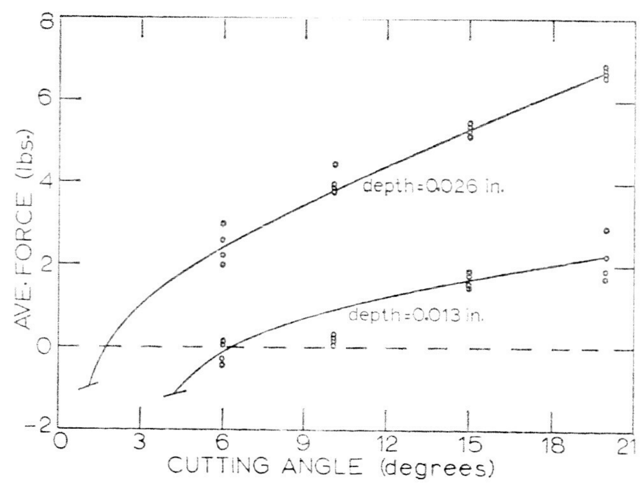

Figure 16. — Average normal force versus cutting angle for two depths of cut.

A study should be made of the effects of a square junction between the planing and shearing edges on the magnitudes of the transverse force.

The effects of cutting angle as related to depth of cut on cutting forces and energy consumption should be thoroughly investigated.

Tests at cutting speeds in excess of 3,640 feet per minute should be conducted to determine the existence of and reasons for the apparent rapid decrease in cutting force and to establish, if it exists, the critical cutting speed.

Literature Cited

1. McKenzie, W. M. 1962. Relationships between the cutting properties of wood and its physical and mechanical properties. For. Prod. Jour. 12 (6): 287-94.
2. ————. 1960. Fundamental aspects of the wood cutting process. For. Prod. Jour. 10 (9): 447-56.
3. ————, and N. C. Franz. 1964. Basic aspects of inclined or oblique wood cutting. For. Prod. Jour. 14 (12): 555-66.
4. Franz, N. C. 1955. An analysis of chip formation in wood machining. For. Prod. Jour. 5 (5): 332-36.
5. Reineke, L. H. 1950. Sawteeth in action. Proc. For. Prod. Res. Soc. pp. 36-52.
6. ————. 1960. Pendulum cutting test standardization. For. Prod. Jour. 10 (10): 542-53.
7. ————. 1960. Pendulum cutting test standardization, Part II. For. Prod. Jour. 10 (11): 571-76.
8. Walker, K. J. S., and R. Goodchild. 1960. Theory of cutting, Part I; Experiments in rectilinear cutting. For. Prod. Res. Spec. Rpt. 14. H. M. S. O., London, England.
9. Randel, W. C. 1952. Cutting characteristics of different power saw chain designs. Michigan State College Agric. Exp. Station Bull. 35 (2): 219-29.
10. McKenzie, W. M. 1955. Performance of gouge type power saw chains. Australian Timber Jour. 21 (10): 938-54, 995.
11. Oehrli, J. W. 1960. Dynamometer tests on cutting action of chain saw teeth. For. Prod. Jour. 10 (1): 4-7.
12. Troeng, I. 1952. Motorsagkedjor Deras Arbetssatt Och Konstruktion. Meddelanden Fran Statens Skogsforskningsinstitut 41 (8).
13. Davis, E. M. 1962. Machining and related characteristics of United States hardwoods. U.S.D.A. Tech. Bull. 1267.
14. Lowen, E. G., E. R. Marshall, and M. C. Shaw. 1951. Electric strain gauge tool dynamometers. Exp. Stress Anal. 8 (2): 1-16.
15. Cook N. H., E. G. Loewen, and M. C. Shaw. 1954. Machine tool dynamometer — a current appraisal. American Machinist. 98 (10): 125-29.
16. Tiemann, H. D. 1906. Effects of moisture upon the strength and stiffness of wood. U.S.D.A. FS Bull. 70.
17. Wilson, T. R. C. 1932. Strength-moisture relations for wood. U.S.D.A. Tech. Bull. 282.
18. Youngs, R. L. 1957. Mechanical properties of red oak related to drying. For. Prod. Jour. 7 (10): 315-24.
19. Black, P. H. 1961. Theory of metal cutting. McGraw-Hill Book Co., Inc., New York, N.Y.

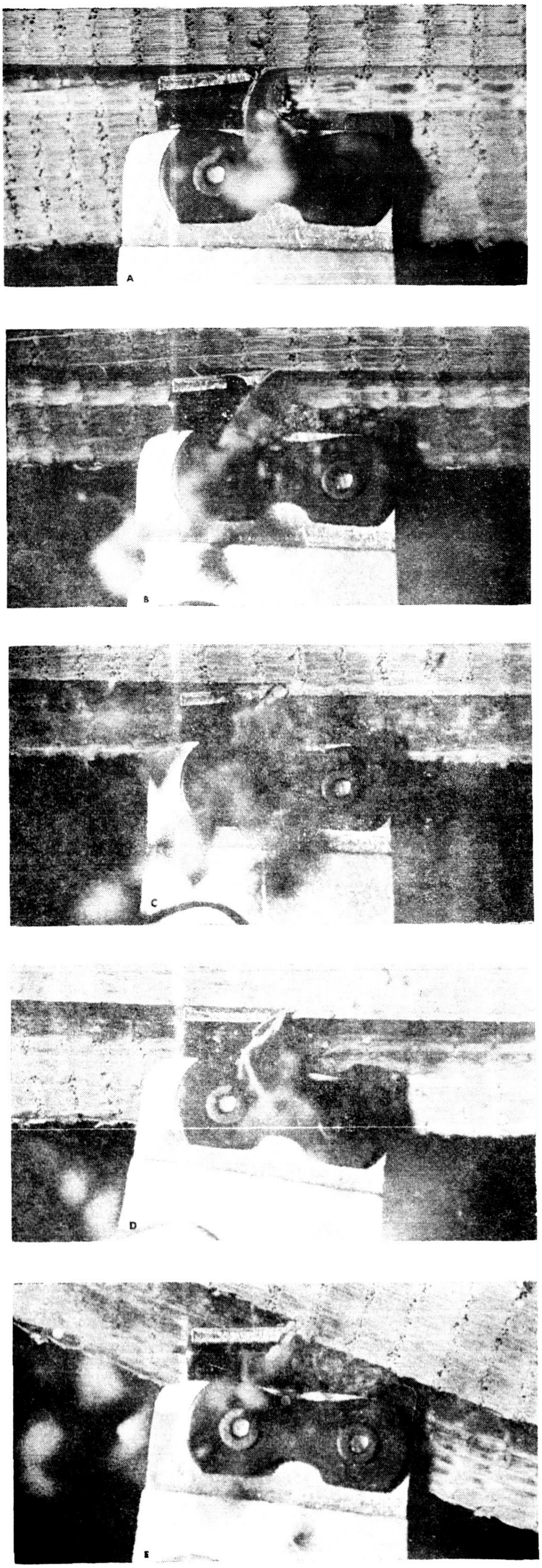

Figure 17. — High-speed photographs of chip formation. a) Chip formation at 0.011 inch depth of cut and 1,040 feet per minute cutting speed with 6° cutting angle. Shows plastic chip. b) Chip formation at 0.010 inch depth of cut and 2,080 feet per minute cutting speed with 6° cutting angle. Shows plastic chip. c) Chip formation at 0.050 inch depth of cut and 2,080 feet per minute cutting speed with 6° cutting angle. Shows riven chip. d) Chip formation at 0.036 inch depth of cut and 1,560 feet per minute cutting speed with 0° cuting angle. Shows chip at approximate transition depth. e) Chip formation of 0.036 inch depth of cut and 1,560 feet per minute cutting speed with 20° cutting angle. Shows chip at approximate transition depth.